## "Plug and play" systems for quantum cryptography

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## Abstract

We present a time-multiplexed interferometer based on Faraday mirrors, and apply it to quantum key distribution. The interfering pulses follow exactly the same spatial path, ensuring very high stability and self balancing. Use of Faraday mirrors compensates automatically any birefringence effects and polarization dependent losses in the transmitting fiber. First experimental results show a fringe visibility of 0.9984 for a 23km-long interferometer, based on installed telecom fibers.

In so-called private-key cryptographic systems, secure transmission through unprotected channels rely on the exchange of secret keys, known only to the sender, Alice, and the receiver, Bob. Quantum cryptography (QC) relies on the properties of quantum mechanics to obtain a provably secure key distribution [1, 2, 3, 4]. Most exisiting implementations rely on either the polarization [2, 5, 6] or the phase [7, 8, 9, 10] of very weak pulses of light as information carrier. To date, the longest transmission spans were obtained in optical fibers, at a wavelength of 1300 nm [6, 9, 10].

The main difficulty with polarization-based systems is the need to keep stable polarizations over distances of tens of kilometers, in standard telecom cables. Indeed, due to the birefringence of the fibers and the effect of the environment, the output polarization fluctuates randomly. Recent experiments [6] have shown that in general the time-scale of these fluctuations is long enough (tens of minutes) to enable polarization tracking to compensate for them. However, while this is no major problem for preliminary experiments, this would be inconvenient for practical applications of QC.

Interferometric quantum key distribution systems are usually based on a double Mach-Zehnder interferometer [9, 10], one side for Alice and one for Bob (see Fig. 1). These interferometers already implement time-multiplexing, as both interfering pulses follow the same path between Alice and Bob, with some time delay. However, the pulses do follow different paths within both Alice's and Bob's interferometers. In order to obtain a good interference, both users therefore need to have identical interferometers, with the same coupling ratios in each arm and the same path lengths, and also need to keep them stable within a few tens of nm during a transmission. Moreover, since optical components like phase modulators (PM) are polarization dependent, polarization control is still necessary both in the transmission line and within each interferometer. This again is inconvenient for practical applications.

In this letter, we present a new interferometric system implementing phase-encoded quantum key distribution [11]. It is based on time-multiplexing, the interfering pulses now following exactly the same spatial path, albeit with a small time delay. Therefore, in contrast to the usual schemes, it does not require any path length control between the various paths. Moreover, all pulses are reflected back at the end of the fibers. Use of Faraday mirrors instead of regular mirrors makes it possible to suppress all birefringence effects and polarization dependent losses occurring during the transmission. Therefore, our system does not require any polarization control. In essence, with our system, Alice and Bob could exchange their

cryptographic keys through standard telecom systems, with no need for lengthy adjustments. They would be provided with a sending kit and a receiving kit, and could simply plug them in at the end of the fiber, synchronize their signals, and start the exchange. This is the reason why we informally refer to our system as a "plug and play" system.

A schematic of the setup is given in Fig. 2. Bob initiates the transmission by sending a short laser pulse towards Alice. Let us for the moment disregard the effects of the Faraday rotators (FR). The need for coupler C3 and detector D<sub>A</sub> in Alice's arm will also be explained later. The pulse arriving in C2 is split into two parts: one part, P1, goes directly towards Alice; while the second part, P2, is first delayed by one bounce in the M2-M1 delay line. The two pulses, P1 and P2, travel down the fiber to Alice. In order to encode her bits, Alice lets P1 be reflected by M3, but modulates the phase of P2. Detection on Bob's side is done by delaying part of P1 in the same M1-M2 delay line (using also another PM, this time on P1), and looking at the interference with P2. If the PMs at both Alice's and Bob's are off, the interference is constructive (the two pulses follow exactly the same path). If however Alice or Bob change their phase setting betwen the two pulses, the interference may become destructive. In fact it is easily seen that destructive interference is obtained when:  $\phi_A - \phi_B = \pi$ , where  $\phi_A$  and  $\phi_B$  are the total phase shifts introduced by Alice and Bob respectively. In this case no light is detected at D0. This shows that the relative phase setup modulates the intensity in D0, and thus can be used to transfer information from Alice to Bob. The first attractive features of this setup are that the interferometer is automatically aligned (both pulses are delayed by the same delay line), and that the visibility of the fringes is independent of the transmission/reflection coefficients of C2. Of course, a large fraction of the light does not follow these two paths, but is split differently at the various couplers (e.g. keeps oscillating a few times between M1-M2 or M1-M3 before leaving towards D0). These pulses will eventually arrive in D0, but at a different time, and will be easily discriminated. Therefore, they do not reduce the visibility.

The above setup would work perfectly well for ideal fibers, with no birefringence. Unfortunately, all existing optical fibers have birefringence and polarization couplings, which will modify randomly the state of polarization of the light, and may lead to a reduction in the visibility of the interference. In order to preserve interference, we replace the mirrors by so-called Faraday mirrors (FM) [12]. A Faraday mirror is simply an ordinary mirror, glued on a Faraday rotator (FR), which rotates the polarization by 45°. The effect of a FM is to transform any polarization state into its orthogonal. The most interesting consequence is that a FM automatically compensates any birefringence effect in the fiber: the state going out of the fiber is alway orthogonal to the incoming state. Replacing the ordinary mirrors M1 and M2 by FMs (i.e. adding the FRs), thus ensures that the two pulses P1 and P2 have the same polarization, irrespective of birefringence effects in the delay line M1-M2. Use of an extra FM in M3 enables to compensate for the polarization dependence of the PM.

Till here, we have only discussed macroscopic pulses. In order to get quantum cryptographic security, the information carrying pulses need to be very weak, with at most one photon per pulse. This is to prevent a malevolent eavesdropper, known as Eve, to divert part of the pulse and get information on the key (see e.g. [2] for more on eavesdropping). In practice, we rely on strongly attenuated laser light, with about 0.1 photon per pulse on average. This attenuation is obtained by adding the extra coupler C3 in Alice's arm. Using detector D<sub>A</sub>, Alice can monitor the intensity of the incoming pulses, and attenuate them to ensure that P2 going back to Bob has indeed the correct intensity (remember that the pulses going from Bob to Alice do not carry any phase information yet; it is only on the way back to Bob that the phase chosen by Alice is encoded in P2). In order to be able to use ordinary detectors, and not single-photon ones, it is preferable for Alice to have a strongly transmitting coupler, with  $t_3 \approx 1$ . This maximizes the intensity going to her detector, as well creating enough attenuation on the beams reflected by M3 to have a single-photon-like pulse sent back to Bob. Monitoring the incoming intensity has the added advantage that Alice can detect any attempt by Eve to obtain the value of her phase shift by sending much stronger pulses in the system, and measuring the phase of the reflected pulses. On Bob's side, detector D0 needs to be a single-photon detector. In order to obtain as much of the light as possible on D0, the coupler C1 has to be mostly transmitting.

Let us now show how this scheme implements the original phase-encoding proposal [7], known also as the two-states system. Both Alice and Bob choose at random their phase settings: 0 or  $\pi$  phase shifts,

corresponding respectively to bit value 0 and 1. If Alice and Bob use different phase shifts, the difference is always  $\pi$ , which means that the interference in D0 is always destructive. So, if Bob chooses bit 0, and gets one count in his detector, he knows that Alice has also sent a 0, and reciprocally for bit 1. Of course, since they use very weak pulses, in many instances Bob would get no count in D0. In this case, he cannot infer what was sent by Alice: it could be that Alice used a different phase; or it could be that there was simply no photon in the pulse. This corresponds to the fact that the two states are not orthogonal, and thus cannot be distinguished with certainty [7]. We can now understand why we do need very weak pulses: if Alice and Bob use strong pulses, which always carry more than one photon, Bob would always know the bit sent by Alice: one count, same choice of phase; no count, different choice of phase. Unfortunately, so would Eve. For example, she could simply add an extra coupler on the line, and measure the phase of the pulses sent by Alice. However, if the pulse sent by Alice possesses at most one photon, this simple eavesdropping strategy fails completely: if Eve measures the photon, then Bob will not get it, and would simply discard the corresponding transmission.

Another eavesdropping strategy on two-state systems, discussed in [7], would be for Eve to stop the transmission altogether, measure as many pulses as she could, and send to Bob only the ones for which she managed to obtain the phase. To prevent this, Alice needs to send both a strong pulse, as a reference, and a weak one, containing the phase information. Eve cannot suppress the strong pulse without being immediately discovered. If she supresses only the weak one, because she did not obtain the phase information, the strong pulse alone will introduce noise in detector D0. In our system, this is easily implemented by using a strongly asymmetric coupler C2, with transmission coefficient  $t_2 \approx 1$ . In this case, P1 going back towards Bob is much stronger than P2, which has already been through the M1-M2 delay line, and thus was strongly attenuated (by a factor  $(r_2)^4$  in the intensity). Bob can detect the part of P1 going directly to detector D0, before looking at the interference. It is also possible to simply add an extra coupler and detector in front of M1, in a way similar to Alice's setup. Further discussion on eavesdropping would be outside the scope of this paper [13].

The same setup, but with different choices of phase for Alice and Bob can trivially be used to implement other protocols, such as the well-known BB84 protocol [2], where Alice chooses between four possible states. A very similar one can also be used for polarization-encoded systems. It suffices to replace the coupler C2 by a polarization coupler (PC2), and send the light with circular polarization. One of the polarization components, say the vertical one, follows the path of P1 (with a polarization switch from vertical to horizontal and vice versa each time it is reflected by a FM), while the horizontal one follows the path of P2. A phase change on Alice's side now corresponds to a different output polarization. This system does not require a second PM on Bob's side, but needs a more complicated detection system, which can separate the various polarizations. Experimentally, we concentrated on the phase-encoded one, which has the simplest detection setup.

Our experiment implements a slightly simplified version of the phase-encoding system. The long arm of the interferometer, which corresponds to the distance between Alice and Bob, is one optical fiber in a 23km long commercial optical cable, used for telecommunications between Nyon and Geneva in Switzerland. The laser produces 300ps long pulses at 1300nm, with a repetition rate of 1kHz. The phase modulator on Bob's side was built with a fiber wrapped around a piezoelectric modulator. This setup has very low losses, but is limited to a few kHz. The length of the M1-M2 delay line is 23m, which corresponds to a time delay of 250ns between the two pulses. On Alice's side, the phase modulator is a Lithium Niobate waveguide, that can be driven up to a GHz. This fast modulation is needed in order to be able to modulate the phase of the second pulse arriving at Alice's, without changing the phase of the first one. One interesting point is that this type of phase modulator is always polarization dependent. However, this polarization dependence is cancelled out, thanks to the Faraday mirrors (the light goes in the PM at some polarization, and again after reflection at M3 with the opposite one). At this stage, we do not insert detector  $D_A$ , but only modulate the phase of the pulse. The visibility of the interference fringes is 0.9984, without any need for adjustments. The system is also totally stable.

During the mere few years since the first experimental demonstration of QC, we have seen tremendous progress. The first setup in 1992 used visible light, over an air gap of about 30 cm. Recent results show that quantum key distribution is possible over distances of tens of kilometers, using only standard telecom

cables. The main experimental challenge is now to demonstrate that QC is practical. Existing systems, while perfectly fine for a demonstration, require careful adjustements and control of the systems on each side of the communication channel. In this letter, we proposed what we call a "plug and play" system, which requires no adjustement at all, except for the timing. Our first experimental results show a very good stability, and high fringe visibility. This shows that our new scheme is indeed very promising for practical implementations of QC. We are currently working on a fully operational prototype.

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## References

- [1] C.H. Bennett, G. Brassard, and A.K. Ekert, Scientific American 267(4), 26 (1992).
- [2] C.H. Bennett, F. Bessette, G. Brassard, and L. Savail, J. Cryptology 5, 3 (1992).
- [3] R.J. Hughes, D.M. Alde, P. Dyer, G.G. Luther, G.L. Morgan, and M. Schauer, *Contemporary Phys.* 36 (3), 149 (1995).
- [4] Special issue on quantum communication, J. Mod. Opt. 40, 1994.
- [5] A. Muller, J. Breguet, and N. Gisin, Europhys. Letts. 23, 383 (1993).
- [6] A. Muller, H. Zbinden, and N. Gisin, Europhys. Letts. 33, 335 (1995).
- [7] C.H. Bennett, Phys. Rev. Lett. 68, 3121 (1992).
- [8] P.D. Townsend, J.G. Rarity, and P.R. Tapster, Electron. Lett. 29, 634 (1993).
- [9] P.D. Townsend, *Electron. Lett.* **30**, 809 (1994).
- [10] R.J. Hughes, G.G. Luther, G.L. Morgan, and C. Simmons. In Proceeding of the Seventh Rochester Conference on Coherence and Quantum Optics, Rochester, NY, 1995.
- [11] N. Gisin, B. Huttner, A. Muller, B. Perny, and H. Zbinden, "Plug and play" systems for quantum cryptography, US Patent pending (1996).
- [12] M. Martinelli, M.J. Marrone, and M.A. Davis, J. Mod. Opt 39, 451 (1992).
- [13] A.K. Ekert, B. Huttner, G.M. Palma, and A. Peres, Phys. Rev. A 50, 1047 (1994).

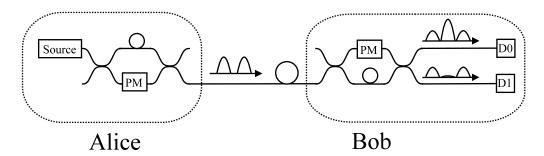


Figure 1: Mach-Zehnder interferometer for QC.

The pulsed laser is split into two time-shifted pulses by Alice: one goes trough the short path (S) and the phase modulator (PM); and the second through the long path (L). Information about the key is encoded in the phase-shift introduced in PM. After propagation, the two pulses arrive into a similar interferometer on Bob's side, creating three pulses. The first one (SS) and the last one (LL) carry no information on the phase settings. The middle one is obtained by interference between two paths: SL and LS. The relative phase settings creates a constructive or destructive interference in D0 and D1. In order to obtain a good visibility, the two interferometers have to be kept identical and should preserve polarization.

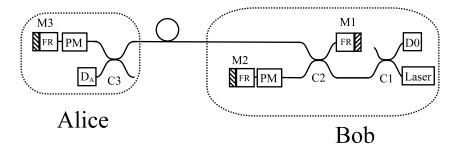


Figure 2: "Plug and play" system with phase-encoding.

A short laser pulse sent by Bob is split into two at coupler C2. The first part, P1 goes straight to Alice, while the second one, P2, is first delayed by the M2-M1 delay line. Both pulses are reflected back towards Bob at M3. Alice measures the intensity of the incoming pulses, and attenuates them to single-photon levels. The phase modulators (PM) modulate the path length between the two pulses. On arrival to Bob's side, part of P1 is delayed by M1-M2, and thus interferes with incoming P2. The interference pattern at D0 gives the relative phase settings of Alice and Bob. Use of the Faraday rotators (FR) before the mirrors makes it possible to cancel out all birefringence effects in the fibers.